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SPIN OBSERVABLES IN NUCLEON-NUCLEUS SCATTERING

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## 1. INTRODUCTION

The curse of inelastic nucleon scattering and charge exchange has always been the enormous complexity of the nucleon-nucleon (N-N) interaction. This complexity, however, can also be viewed as the ultimate promise of nucleons as probes of nuclear structure. Given an adequate theoretical basis, inelastic nucleon scattering is capable of providing information not obtainable with other probes.

Recently a revolution of experimental technique has taken place that makes it desirable to re-examine the question of what physics is ultimately obtainable from inelastic nucleon scattering. It is now feasible to perform complete polarizaton transfer (PT) experiments for inelastic proton scattering with high efficiency and excellent energy resolution. Programs to measure PT observables are underway at several laboratories, and results are beginning to appear. Objectives of this talk are to examine how such experiments are done, and what physics is presently obtained and may ultimately be learned from them.

## 2. POLARIMETRY WITH MEDIUM-ENERGY PROTONS

Availability of medium-energy protons is the crucial factor in the measurement of PT observables in the (p,p') reaction. The long range of protons with energies above 100 MeV makes feasible the design of polarimeters with scattering efficiencies in the range of 0.1% to 10%; this is several orders of magnitude larger than is possible at low energies. When coupled to high-resolution magnetic spectrometers these instruments are ideal for PT measurements. The most advanced system at present is the focal-plane polarimeter on the high-resolution spectrometer (HRS) at LAMPF.[1] A less ambitious polarimeter is attached to the focal plane of the QDDM spectrometer at IUCF.[2] The latter system has the advantage of a very high intensity (150 nA) polarized proton beam.

The LAMPF-HRS polarimeter (Fig. 1) consists of a pair of planes of x- and y-sensitive multiwire drift chambers (MWDC) and associated scintillators, which constitute the normal focal-plane array. Following this the protons are scattered from 12 cm of carbon, and detected by two additional planes of larger MWDC's and scintillators. Thus for each proton, the initial and final (after scattering from the carbon block) trajectories are determined. From this information the scattering angle in both planes perpendicular to the outgoing momentum may be deduced. The data-acquisition system includes a fast micro-processor front end, which rejects protons that do not scatter in the carbon block. A flexible system of initial polarization orientation in the LAMPF accelerator allows one to measure all possible PT observables (because of spin precession in the field of the HRS, not all observables can be measured for all outgoing energies). Those consistent with parity conservation are $D_{NN}$, $D_{LL'}$, $D_{SS'}$, $D_{LS'}$, and $D_{SL'}$; where L, N, and S are respectively in the direction of the incident momentum, $\vec{k}$, normal to the reaction plane (along $\vec{k} \times \vec{k}'$), and normal to $\vec{k}$, in the reaction plane ($\vec{N} \times \vec{L} = \vec{S}$). Final (primed) subscripts are defined analogously with respect to the final momentum, $\vec{k}'$.

One additional observable that will prove to be very interesting is the polarization function, P, or more precisely, P-A, where A is the analyzing power. Measurement of P is accomplished by measuring

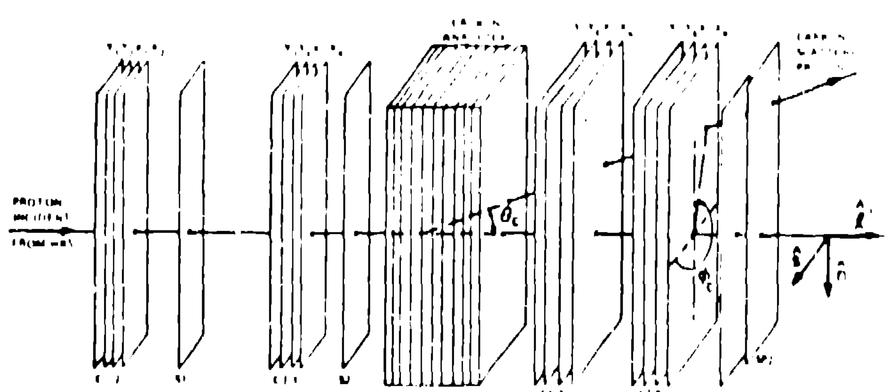

Fig. 1. Schematic of the HRS focal-plane polarimeter.

the outgoing polarization in a reaction induced by an unpolarized beam.

## 3. THEORETICAL FRAMEWORK

Now that one can measure these new observables, it is fair to ask, "What do they tell us?" We will address this question from a simple viewpoint that displays the physics involved in a fashion that is much more transparent than one gets from numerical calculations with either the distorted-waves impulse approximation (DWIA) or the Glauber model.

In the plane-wave impulse approximation (PWIA), the N-nucleus scattering amplitude is

$$\bar{M}_\mu(q) = \langle \mu \mid M(q)\, e^{-i\vec{q}\cdot\vec{r}} \mid 0 \rangle$$

where M(q) is the N-N scattering amplitude, and $\mu$ is the projection of the total angular momentum transfer along the q axis. Following Kerman, McManus, and Thaler [3](KMT)

$$M(q) = A + B\,\sigma_{1\hat{n}}\sigma_{2\hat{n}} + C(\sigma_{1\hat{n}}+\sigma_{2\hat{n}}) + E\sigma_{1\hat{q}}\sigma_{2\hat{q}} + F\sigma_{1\hat{p}}\sigma_{2\hat{p}} \qquad (1)$$

with

$$\hat{q} = \vec{q}/q \qquad \vec{q} = \vec{k} - \vec{k}'$$

$$\hat{n} = \vec{n}/n \qquad \vec{n} = \vec{k} \times \vec{k}'$$

$$\hat{p} = \vec{p}/p \qquad \hat{p} = \hat{n} \times \hat{q}$$

### 3.1 Unnatural Parity States

First we consider the excitation of unnatural parity states. We using the expression

$$D_{ij} = \sum_\mu \mathrm{Tr}(\bar{M}_\mu \sigma_i \bar{M}_\mu^{+} \sigma_j) \,/\, \sum_\mu \mathrm{Tr}(\bar{M}_\mu \bar{M}_\mu^{+}) \qquad (2)$$

one arrives at simple expressions for the PT observables in the $\hat{n},\hat{p},\hat{q}$ system[4] ($\hat{n}$ is indentical to N)

$$
\begin{aligned}
\sigma_o D_{\hat{n}\hat{n}} &= X_T^2\,(C^2 + B^2 - F^2) - X_L^2\,E^2 \\
\sigma_o D_{\hat{p}\hat{p}} &= X_T^2\,(C^2 - B^2 + F^2) - X_L^2\,E^2 \\
\sigma_o D_{\hat{q}\hat{q}} &= X_T^2\,(C^2 - B^2 - F^2) + X_L^2\,E^2 \\
\sigma_o D_{\hat{q}\hat{p}} &= -\sigma_o D_{\hat{p}\hat{q}} = 2X_T^2\,\mathrm{Im}\,(BC^*)
\end{aligned}
\qquad (3)
$$

where the differential cross section, $\sigma_o$ , is given by

$$\sigma_o = X_T^2\,(C^2 + B^2 + F^2) + X_L^2\,E^2 \quad .$$

The transverse, $X_T$, and longitudinal form factors, $X_L$ are defined by

$$
\begin{aligned}
X_T &= \left(\frac{j+1}{2(2j-1)}\right)^{1/2} Q_{jj-1} + \left(\frac{j}{2(2j+3)}\right)^{1/2} Q_{jj+1} \\
X_L &= \left(\frac{j}{(2j-1)}\right)^{1/2} Q_{jj-1} - \left(\frac{j+1}{(2j+3)}\right)^{1/2} Q_{jj+1} \quad ,
\end{aligned}
\qquad (4)
$$

where $Q_{j\ell}$ is a reduced matrix element defined in Appendix III of KMT. Transformation of Eqs. (3) to the laboratory system (N, L, S, S', L') is straightforward[4]. Equations (3) may be inverted to yield

$$
\begin{aligned}
X_L^2 &= \sigma_o/4E^2\,(1 - D_{\hat{n}\hat{n}} + D_{\hat{q}\hat{q}} - D_{\hat{p}\hat{p}}) \\
X_T^2 &= \sigma_o/4B^2\,(1 + D_{\hat{n}\hat{n}} - D_{\hat{q}\hat{q}} - D_{\hat{p}\hat{p}}) \\
X_T^2 &= \sigma_o/4C^2\,(1 + D_{\hat{n}\hat{n}} + D_{\hat{q}\hat{q}} + D_{\hat{p}\hat{p}}) \\
X_T^2 &= \sigma_o/4F^2\,(1 - D_{\hat{n}\hat{n}} - D_{\hat{q}\hat{q}} + D_{\hat{p}\hat{p}}) \\
X_T^2 &= \sigma_o/2\mathrm{Im}\,(BC^*)\,D_{\hat{q}\hat{p}} \quad .
\end{aligned}
\qquad (5)
$$

Note that with the knowledge of the coefficients of the impulse approximation (IA) interaction, the PT observables may be used to directly infer these two form factors.[5] The transverse form factor is similar to that obtained from electron scattering. However, $X_L$ is not present in (e,e') and thus represents a new aspect of nuclear structure obtainable in (p,p') experiments. Of course the separation of nuclear structure and reaction dynamics is not straightforward in the DWIA. However, the physics contained in Eqs. (3) and (5) must still be present.

It often occurs that a given transition is dominated by a single $\ell$ value, e.g., in stretched configurations. Then $X_L$ = $X_T$ (apart from constants) and Eqs. (3) for the PT observables become independent of nuclear structure. In such cases the $D_{ij}$'s may be used to deduce the components of the effective N-N interaction. Evidence is accumulating that certain parts of this interaction may differ considerably from the free N-N interaction.[6]

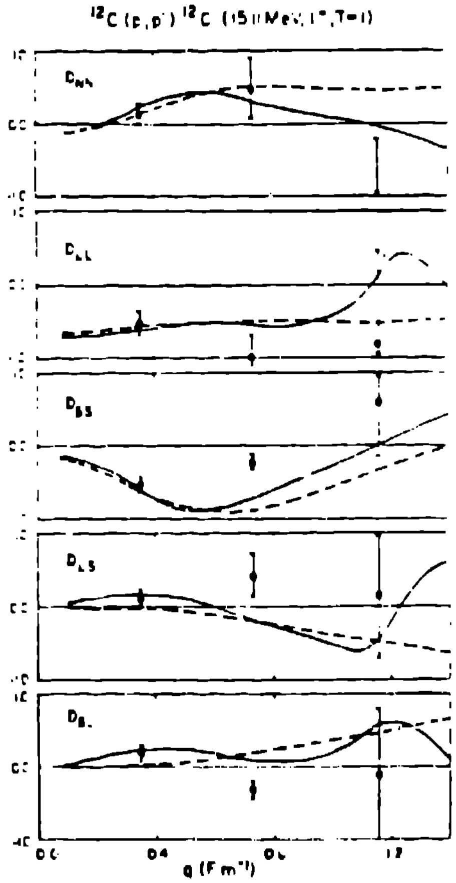


Fig. 2. Polarization transfer observables (preliminary analysis) at $E_p$ = 500 MeV.

By comparing to exact DWIA calculations we have found that the approximations that yield the simple equations are reasonably accurate for $q < 1\ fm^{-1}$. Figure 2 shows such a comparison along with experimental data for the $^{12}C(p,p')^{12}C$ (15.11 MeV, $1^+$, T=1) reaction at 500 MeV.[7]

## 3.2 Natural Parity Transitions

For natural parity transitions we consider only the case where a single j transfer is allowed, such as for transitions from a $0^+$ ground state. Form factors with and without spin transfer are allowed; $Q_{j\ell}$ and $Q_j$ respectively. Natural parity transitions are often dominated by a collective spin-independent amplitude. Intuition would say that in such cases, the effects on the PT observables from the spin-dependent form factor might be difficult to measure. Equations derived from (2) are best cast in the form of a spin-flip probability (SFP), where $S_{ij} = 1/2\ (1-D_{ij})$. One finds

$$
\begin{aligned}
S_{\hat{n}\hat{n}} &= Q_{j\ell}^2\ F^2\ /2\sigma_o \\
S_{\hat{q}\hat{q}} &= Q_{j\ell}^2\ (B^2 + F^2)\ /2\sigma_o \\
S_{\hat{p}\hat{p}} &= Q_{j\ell}^2\ \ B^2\ /2\sigma_o \qquad\qquad (6) \\
S_{\hat{q}\hat{p}} &= 1/2\ \left[1 - 1/2\ Q_{j\ell}^2\ \mathrm{Im}\ (BC^*) + 2Q_j^2\ \mathrm{Im}\ (AC^*)\right] \\
\sigma_o &= 1/2\ Q_{j\ell}^2\ (C^2 + B^2 + F^2) + Q_j^{\ 2}(A^2 + C^2)\ .
\end{aligned}
$$

Clearly the diagonal SFPs are different from zero only to the extent that the spin-transfer form factor, weighted by the spin-dependent terms of the N-N interactions, competes with the corresponding spin-independent factors.

## 3.3 Polarization and Analyzing Power

Evaluation of the polarization and analyzing power in the PWIA yields the result, P = A. As was shown by Squires[8] many years ago, this is a consequence of using a scattering amplitude, which depends only on q. Spin-orbit distortion effects eliminate this equality in the DWIA, but in general P and A have similar shapes unless one is close to a diffraction minimum. A much more interesting difference between P and A arises from the nonlocal/exchange nature of the N-N interaction.[9] In particular, the exchange amplitudes of the tensor interaction yield opposite signs for P and A. In the excitation of the 15.11-MeV state of $^{12}C$ at 150 MeV, the unnatural parity amplitude $\ell sj$ = 111 is the source of most of the difference between P and A. This can be seen in Fig. 3, where PWIA calculations using the code DWBA-70[10] are shown. One set of curves employs the full Cohen-Kuruth[11] (CK) functions; the other uses the CK-wave functions with the $\ell sj$ = 111 term removed. All exchange terms are present in both calculations; plane waves were used in order to isolate the P-A terms from tensor exchange.

## 4. EXPERIMENTS: PRESENT AND FUTURE

Experiments in which PT observables are measured are relatively new and as such few published results exist. We will discuss some of these experiments, often with preliminary data and interpretations, and speculate about areas of future interest.

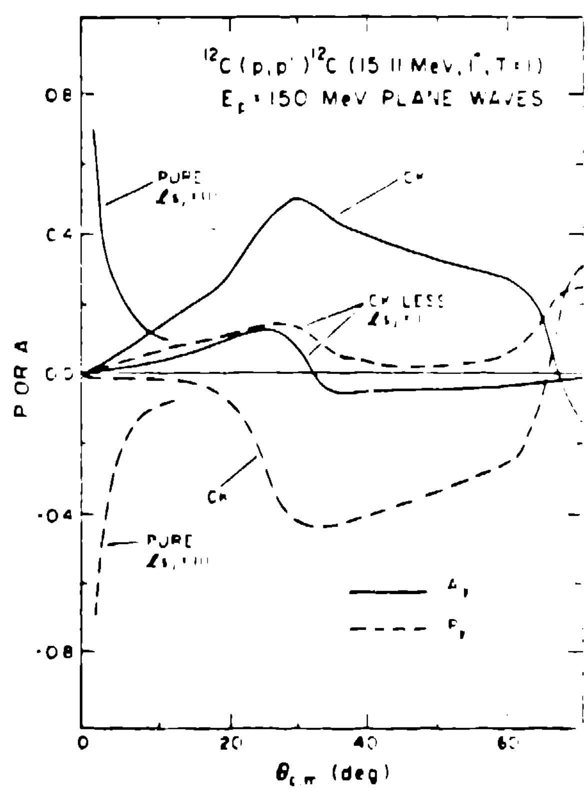


Fig. 3 Plane-wave calculations of P and A. CK stands for the Cohen-Kurath wave functions.

## 4.1 Complete Polarization Transfer Experiments

Recently at LAMPF we have measured the first complete set of PT observables[7] for the excitation of unnatural parity states in $^{12}C$. At small momentum transfer where the data are most precise, the two $1^+$ states of $^{12}C$ are dominated by $\ell sj$ = 011 transfer. Thus equations (3) can be reduced to

$$\bar{C}^2 = 1/4\ (1 + D_{\hat{n}\hat{n}} + D_{\hat{p}\hat{p}} + D_{\hat{q}\hat{q}})$$
$$\bar{B}^2 = 1/4\ (1 + D_{\hat{n}\hat{n}} - D_{\hat{p}\hat{p}} - D_{\hat{q}\hat{q}})$$
$$\bar{F}^2 = 1/4\ (1 - D_{\hat{n}\hat{n}} + D_{\hat{p}\hat{p}} - D_{\hat{q}\hat{q}}) \qquad (7)$$
$$\bar{E}^2 = 1/4\ (1 - D_{\hat{n}\hat{n}} - D_{\hat{p}\hat{p}} + D_{\hat{q}\hat{q}})$$

where $\bar{B}^2 = B^2 / (B^2 + C^2 + E^2 + F^2)$ etc. .

The magnitude of the cross section is not accounted for by the PWIA, hence, it is preferable to compare the experimental and theoretical amplitudes[12] in terms of the normalized (barred) quantities. This comparison is shown in Figs. 4 and 5; experimental data for the 15.11 MeV, state are shown in Fig. 2 along with the DWIA and PWIA curves calculated with the Love-Franey amplitudes. Data are still preliminary so it is not possible to draw firm conclusions. However, this is an indication of a possible problem with the isoscolar spin-orbit amplitude ($C_o$). Recently, independent evidence [13] for a need to increase the spin-orbit amplitude with respect to the IA value has been found in an elastic scattering experiment at 500 MeV.

Clearly, when experiments such as this become even more refined, current reaction theories will be put to severe tests. Our prejudice is that the real future of complete PT experiments is in testing models of nuclear structure at a level not previously possible.

## 4.2 Polarization and Analyzing Power

It is clear from Figs. 6 and 7 that large differences between P and A have been observed in the excitation of the $1^+$ states in $^{12}C$ at 150 MeV.[14] At scattering angles smaller than 20°, P-A is dominated by the effects of tensor exchange discussed in section 3.3. The solid curve in Fig. 6 is a DWIA calculation using the Love effective interaction [15] and the CK wave functions. The dashed wave is a similar calculation with the $\ell sj$ =111 term

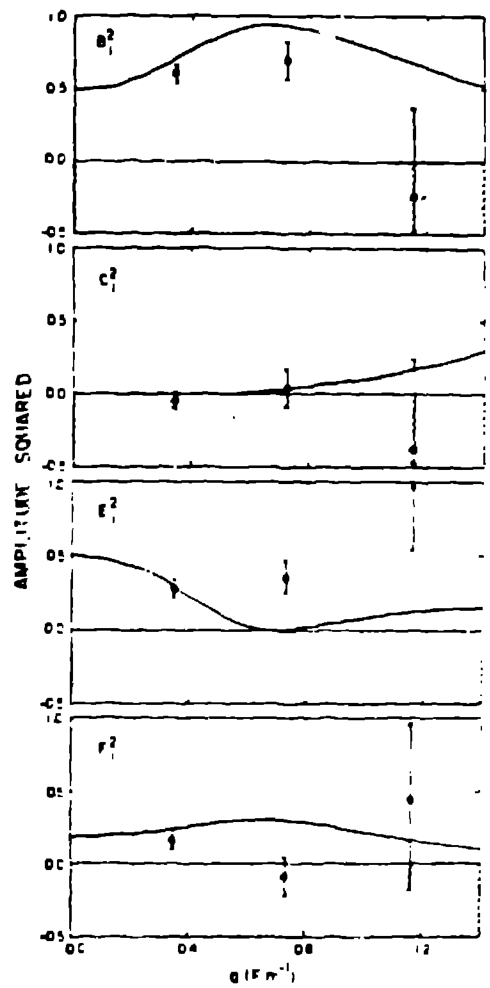


Fig. 4 Isovector impulse approximation amplitudes derived from polarization transfer data (preliminary analysis) at 500 MeV. The solid curves are the Love-Franey amplitudes.

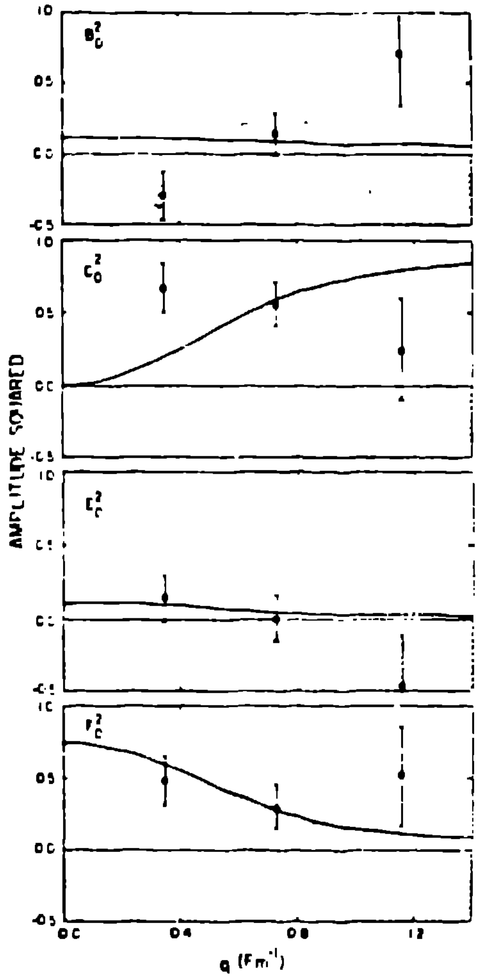

Fig. 5 Isoscalar impulse approximation amplitudes derived from polarization transfer date (preliminary analysis) at 500 MeV. The solid curves are the Love-Franey amplitudes.

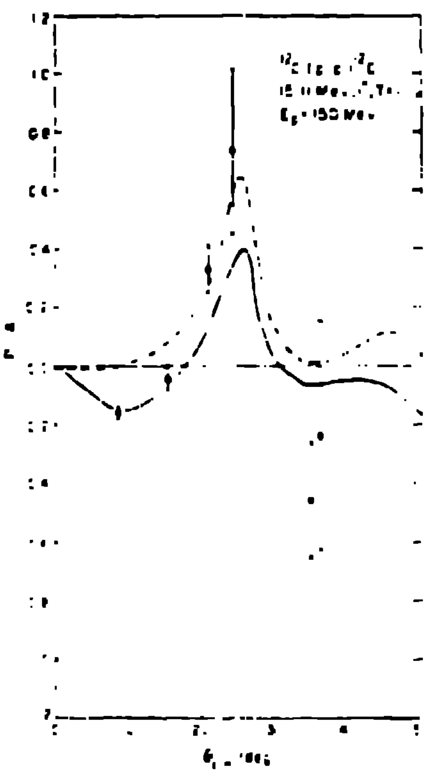

Fig. 6 P-A data versus DWIA calculations using the Cohen-Kurath wave functions (solid curve) and the Cohen-Kurath wave functions with the $\ell sj$ = 111 term removed (dashed curve).

removed. Our preliminary conclusion is that the $\ell sj = 111$ term in the CK wave functions is required to fit the small angle points. We consider these points more significant since the cross section is large here. Additionally, variations in the magnitude of P-A at larger angles are possible due to small changes in optical potential distortions.

The $\ell sj = 111$ term determines the sum of the density matrix elements, $P_{1/2}\, P_{3/2} + P_{3/2}\, P_{1/2}$. As was pointed out by Dubach and Haxton[10] this quantity is very poorly determined by electromagnetic and weak interaction data on the 15.11 MeV state and its analogues. Thus the (p,p') reaction is able to make a unique contribution to the determination of the structure of this transition.

Figure 7 shows that large values of P-A are also seen in the excitation of the $1^+$, T=0 state. The uncertainties in the knowledge of the interaction in the s=1, T=0 channel are such that no definitive statement can be made at this time regarding the

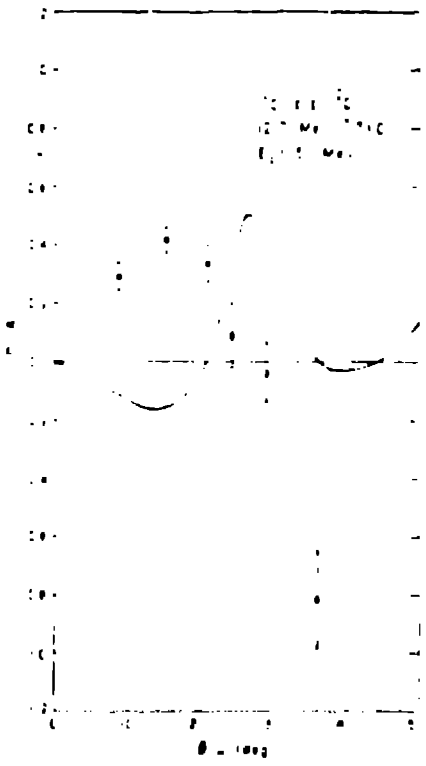

Fig. 7 P-A data versus DWIA calculations with the Cohen-Kurath wave functions.

large discrepancy between calculation and experiment. Further study of the new polarization observables should eventually lead to an u: ``rstanding of the failure of the DWIA to reproduce the angular distribution of this state in the energy range of 150 MeV

## 4.3 Polarization Transfer and Spin Excitation

It is clear from the discussion in Section 3 that the spin observables $D_{\hat{n}\hat{n}}$, $D_{\hat{q}\hat{q}}$, and $D_{\hat{p}\hat{p}}$ are different from unity (and the corresponding SFPs are different from zero) only when spin excitations are important. This rule has had considerable experimental verification both at low [17] and intermediate energies in the case of $D_{\hat{n}\hat{n}}$. Figure 8 shows $S_{\hat{n}\hat{n}}$ for several states in $^{12}C$ excited by 400-MeV protons. Note that the collective $3^-$ state displays a SFP close to zero.

The simple connection between the PT observables and spin transfer means that they can be used to search for spin excitation in unexplored territory. Although $^{12}C$ from $E_x$ = 8 to 20 MeV can hardly be considered such a case, Fig. 9 indicates how a spectrum of spin flip might be used to "amplify" the signal for

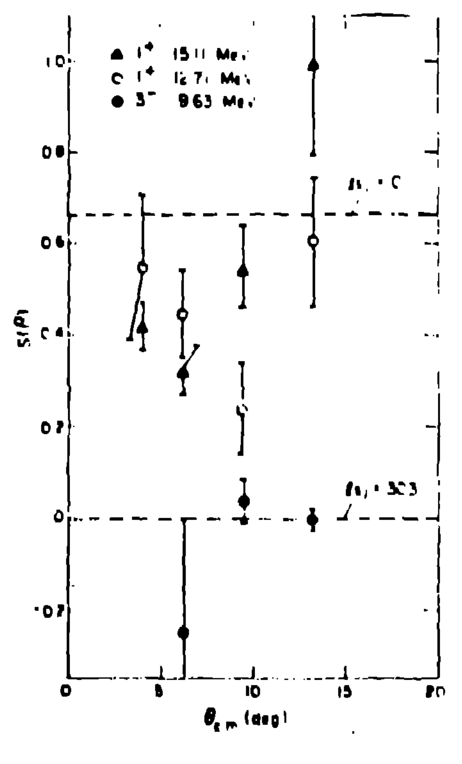


Fig. 8 Spin-flip probabilities for these states in $^{12}C$ at $E_p$ = 500 MeV.

spin excitations. Such experiments are only beginning, hence, we will discuss only one result, and indicate some areas where PT observables may elucidate new physics.

Figure 10 shows data for $A_y$ and $S_{\hat{n}\hat{n}}$ for the (p,p') excitation of the continuum in the range $5 \leq E_x \leq 50$ MeV. The continuum analyzing power is very close to the values for free n-p and p-p scattering, an indication of the dominance of single-step quasi-free scattering. The SFPs, however, are for below the N and Z weighted average of the N-N quantities. Because of the connection between spin flip and spin transfer these data imply a dearth of spin-dependent compared to spin-independent excitation in the low-energy contimuum. Identifiable giant resonances (GR) contribute no more than 10% of the cross section and therefore cannot account for the data. It is still unclear whether the anamalously low SFPs imply spin-independent collectivity, possibly in the form of unresolved GRs, a more exotic explanation, e.g. delta-hole configurations, or some other mechanism. It is clear, however, that more experiments of this type, with statistical precisions good enough to examine smaller intervals of excitation energy, are necessary to provide the answer.

## 4.4 Spin Observables in the Vicinity of Spin-Flip Resonances

Where is the missing M1 and Gamow-Teller (GT) strength in heavy nuclei? The answer has an obvious impact on the understanding of

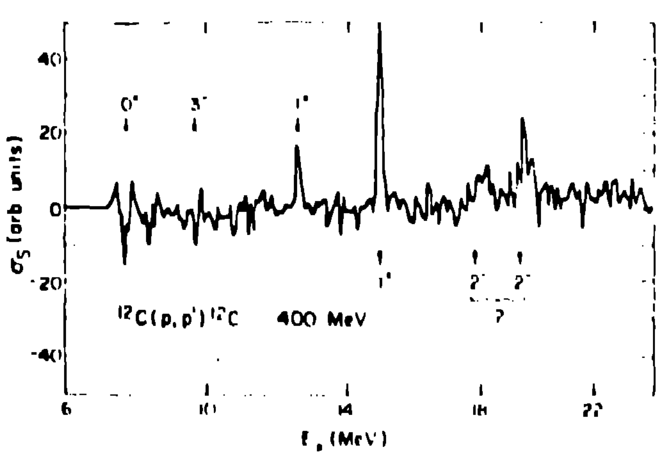


Fig. 9 Spin flip cross section for $^{12}$C at 3.5°.

some very important issues in nuclear structure, including the exciting possibility of delta-hole configurations in low-energy spectra. Measurement of spin observables in the vicinity of the resonances should provide important information about the missing strength. As an example, if the continuum near the GT resonance contained some of the missing strength, one might see an enhancement of, say $S_{\hat{n}\hat{n}}$. Another case is the M1 resonance in $^{90}Zr$. Here the distribution of strength as seen by electron[18] and proton[19] scattering are in serious disagreement. If, as has been suggested, the M1 peak in the (p,p') reaction contains strength other than M1, such a contaminant might be uncovered by measuring the spin observables. Experiments to examine $S_{n\hat{n}}$ in the continuum in both the (p,n) and (p,p') reactions are planned at IUCF and LAMPF.

## 4.5 Spin Observables and Reaction Mechanisms

It has been appreciated for some time that PT observables can be employed as probes of reaction mechanisms.[17] For example, an $0+ \rightarrow 2^-$ transition proceeding by $\ell sj = 112$ transfer from a

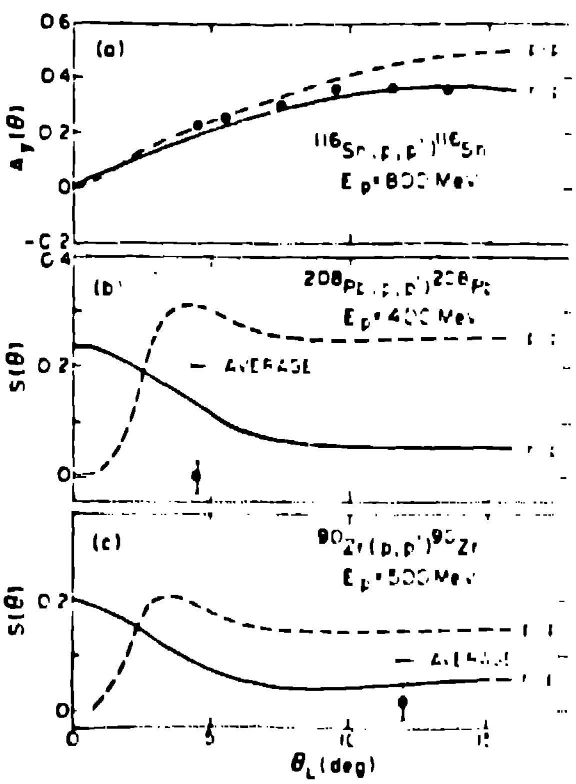


Fig. 10 Analyzing powers and spin-flip probabilities for the continuum near the quasi-elastic peak.

purely central interaction ($B = E = F$, $C = 0$ in Eq. 3) yields $S_{\hat{n}\hat{n}} = 7/10$ in the PWIA. A purely two-step mechanism of the type $0^{+} \rightarrow 3^{-} \rightarrow 2^{-}$ proceeding by two nonspin transfer scatterings yields $S_{\hat{n}\hat{n}} = 0$. More realistic DWIA and coupled-channel calculations bear out the qualitative features of the PWIA. Exceptions may occur in reactions where the two-body, spin-orbit interaction is of major importance.

## 4.6 Spin Observables and Meson Exchange

Bugg has pointed out[20] in connection with searches for precursors of pion condensation [21] that the dominance of certain meson fields in the effective N-N interaction will lead to definite signatures in the PT observables. Although no evidence of precursor phenomena [22] have been found, Bugg's ideas are interesting to consider. As an example, pure one-pion exchange yields $D_{\hat{n}\hat{n}} = -1$, $D_{SS'} = 1/2 \cos\theta$, and $D_{LL'} = -1/2 \cos\theta$; $\rho$ exchange results in a different combination. It may be possible to select transitions which, in selected regions of q, are dominated by nearly pure meson exchange.

## 5. Conclusion

I hope that it has become clearer that we are on the verge of a new era in inelastic proton scattering and charge exchange. Polarimetry has developed to the point where all of the allowed PT observables may be measured with very high efficiency. The simple expressions for these observables presented here make it clear that in certain stiuations new nuclear structure information may be obtained, while in others reaction mechanism may be the dominant effect. It is clear that in the future elucidations of spin excitations in nuclei the new spin observables will play an increasingly important role.

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